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Preliminary Results on an Annular Field Reversed Configuration Translation Experiment

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Carrie S. Hill*

ERC, Inc., Edwards AFB, CA, 93524, USA

Abstract: Annular field reversed configuration (AFRC) devices form annular plasma toroids between a pair of concentric cylindrical coils. The plasma toroid (plasmoid) remains detached from the external magnetic field so that it can be ejected from the coils, making AFRCs potential pulsed inductive plasma accelerators. Though numerous formation studies on AFRCs are available, no successful translation studies have been published. Michigan Technological University, in conjunction with the Air Force Research Laboratory, is investigating the translation of AFRCs as pulsed inductive plasma accelerators. The experiment, the XOCOT-T3, uses a 9 kHz RLC circuit with multi-turn copper coils to form and accelerate the plasmoid. Magnetic $b \cdot \dot{b}$ probes along the device record the magnetic field on the inner and outer radii of the annulus. Rogowski current monitors measure the current through the coils and are used to estimate the energy deposition into the plasma. Images from a high speed camera provide information about gross plasmoid behavior. XOCOT-T3 was tested from 100 J to 500 J with an Argon background gas fill from 1 mTorr to 20 mTorr. Details on formation at 500 J and 4 mTorr show that while a field reversed configuration is created, the plasmoid does not translate. Instead, the plasmoid appears to be limited in lifetime to 10 μ s, extinguishing before it has a chance to translate.

*PhD Candidate, Mechanical Engineering (Michigan Technological University) ,csniemel@mtu.edu

I. Introduction

Pulsed inductive plasma accelerators produce robust, high power-density plasmoids with detached magnetic fields which can be accelerated to high velocities. Inherent to their pulsed nature, they can be throttled for variable thrust and specific impulse with little change in efficiency. Formation through inductive methods minimizes electrode erosion, ensuring longevity.¹ Additionally, they can be used with a variety of propellants and scaled to various sizes to match mission requirements. These characteristics make them attractive for high power electric propulsion.

Pulsed inductive plasmoid accelerators use a variety of formation schemes to form the plasmoid. The plasmoid can be formed using a flat plate coil as was demonstrated in the Pulsed Inductive Thruster (PIT)² and conical variant, the FARAD.³ The plasmoid can be formed in a simple conical geometry using theta-pinch methods as was done in the Plasmoid Thruster Experiment (PTX) and the new generation PTX, the PT-1.⁴

The plasmoid can also be formed using slow-formation techniques such as a rotating magnetic field in the Electroless Lorentz Force (ELF) thruster⁵ or using an annular geometry (AFRC) as shown in Figure 1. All of these devices accelerate their plasmoid or plasma sheet using a Lorentz force ($\mathbf{J} \times \mathbf{B}$) imparted by an external radial magnetic field and azimuthal plasma current.

All variants of pulsed inductive plasmoid accelerators have demonstrated plasmoid translation, with the exception of the annular geometries or the annular field reversed configuration (AFRC). Numerous formation studies have been conducted on AFRCs,^{6,7,8} but before AFRCs can be realized as a high power electric propulsion technology their plasmoid translation must be characterized. The XOCOT-T3 experiment at the U.S. Air Force Research Laboratory-Edwards, in collaboration with Michigan Technological University, has been constructed to demonstrate the translation of AFRC plasmoids. This experiment seeks to measure the translation properties of an AFRC plasmoid, including its velocity, momentum, and acceleration efficiency.

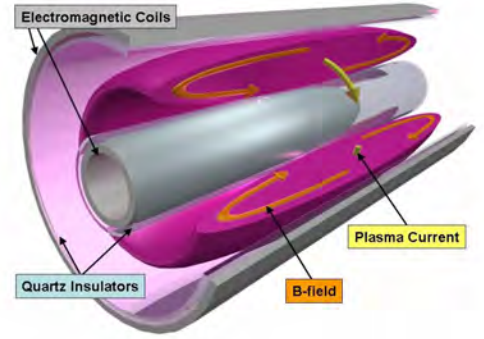


Figure 1. AFRCs are formed inductively between two coaxial coils as shown.

II. Background: AFRC Formation Dynamics

An annular field reversed configuration is a compact plasma toroid formed in the annular region between two coaxial coils. It is a low-voltage derivative of the traditional FRC which is formed without an inner coil. The coils induce a toroidal (azimuthal) diamagnetic current in the plasma, setting up a closed poloidal \mathbf{B} -field. Like other compact toroids, this closed \mathbf{B} -field confines the plasma and allows it to be ejected as a whole from its formation chamber.

The XOCOT-T3 operates with both coils in parallel so that the voltages on each coil rise and fall together, though it is possible to run the coils independently. Figure 2 displays the circuit configuration, typical current waveforms, and the formation sequence for the parallel coil operation. The channel between the coils is filled with an inert gas (Step 1), which is then partially ionized or pre-ionized (Step 2). The main capacitor bank is then discharged, generating azimuthal currents in the coils. The resulting magnetic field is a superposition of the inner and outer coil fields. Since the field outside the inner coil is nearly zero, the field is dominated by the contribution from the outer coil (Step 3). As a consequence of Faraday's Law, the rising field in the annulus causes a current to develop in the plasma to oppose the change in field (Step 4). This current is diamagnetic such that it creates a closed \mathbf{B} -field topology to confine the plasma, reversing the field next to the inner coil. Further increasing the currents in the coils causes the current in the plasma to increase, ionizing and heating it. External magnetic pressure from both coils balances with the plasma pressure to help keep the toroid well-centered in the annulus.

Once the plasmoid is formed, it can be translated from the coils. Generally, this is done using a conical outer coil to produce a small radial magnetic field component. The radial magnetic field component interacts with the largely azimuthal plasma current to drive the plasmoid out of the coils using a Lorentz ($\mathbf{J} \times \mathbf{B}$) force.

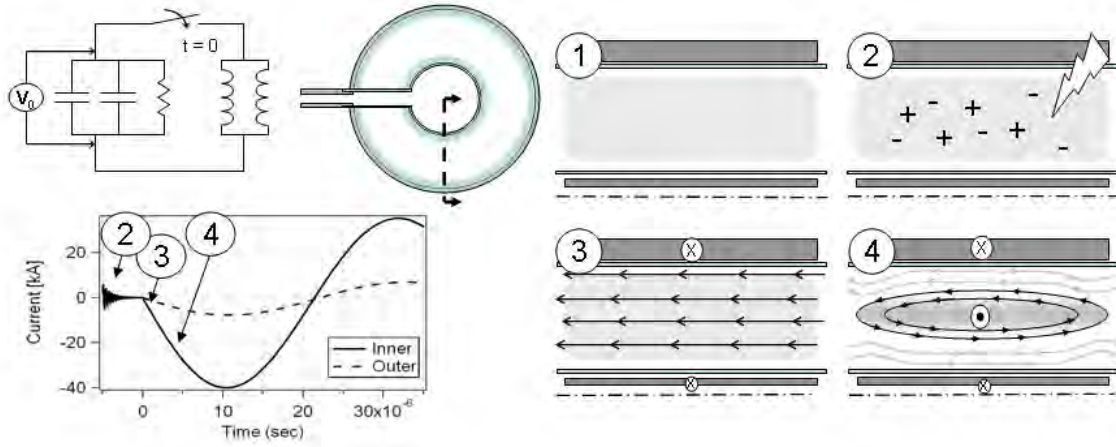


Figure 2. AFRC formation sequence for parallel coils.

III. AFRC Experiment and Diagnostics

The XOCOT-T3 is a single pulse demonstration of AFRC formation and translation, connected to Chamber 5B at the U.S. Air Force Research Laboratory. A photograph of the experiment is shown in Figure 3. The experiment used two separate circuits for the pre-ionization and main bank discharge. The inductive formation allows all circuit components to remain at atmosphere. Optically isolated and triggered switches control firing of the pre-ionization and main bank circuits. The timing on the experiment and data acquisition was controlled through a single 4-channel pulse generator and was triggered manually.

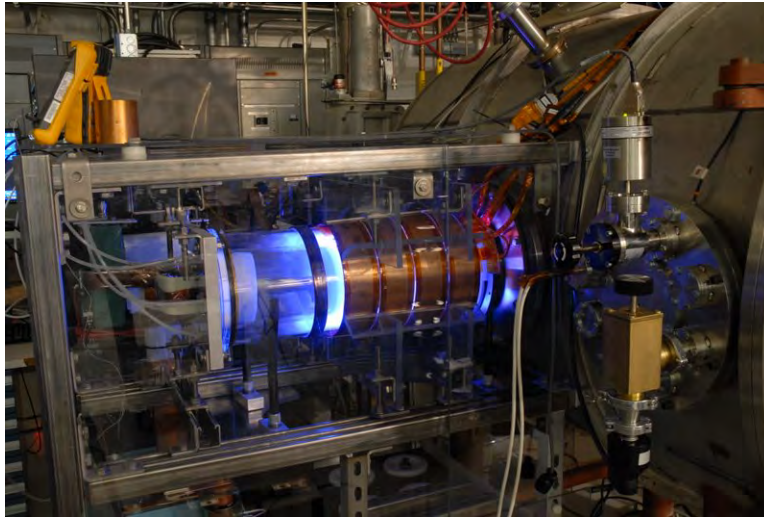


Figure 3. The XOCOT-T3 experiment, connected to Chamber 5B. Image is a long exposure photograph of a single pulse discharge in Argon.

The XOCOT-T3 forms the plasmoid in a static background gas fill. Tests for this work used argon, seeded with 2 percent hydrogen. The gas was dispensed through five ports on the backplate, adjusted using a mass flow controller. The pressure of the gas was monitored on a calibrated MKS Baratron Capacitance Manometer (p/n 627B) connected to the main chamber. The chamber was evacuated through a turbomolecular pump, protected by a mostly closed gate valve. Several hours before testing, the chamber was pumped to 2×10^{-5} Torr to remove impurities. During testing, the gas feed rate was adjusted to match the pressure measured by the capacitance manometer to within 2 percent of the pressure desired for the gas fill.

The pre-ionization (PI) plasma was created using a 2 Joule, 1 MHz ringing theta discharge through a

single antenna, located 1 inch upstream of the coils. The PI circuit was pulsed 20 μs before the main bank and could be varied from pulse to pulse. The capacitor bank for this circuit used six 5-nF ceramic capacitors in parallel to retain a high-Q pulse. The capacitors were switched through a 16 kV, 9000 A compact thyristor stack. The antenna and feedlines were 20-mil copper sheets, insulated with heat shrink and kapton tape and tightly sandwiched together to minimize parasitic inductance. The seed electrons required for breakdown were created using a simple 2-kV DC glow discharge. The DC glow was required as the PI plasma and AFRC plasmoid would not form without it.

The XOCOT-T3 formed the plasmoid between two concentric 4-turn copper coils. The outer coil had a nominal radius of 4.75 inches and the inner coil had a radius of 3 inches. Both coils were 12 inches in length. The coils were hand wrapped from copper sheet, sized to allow for 2-3 skin depths of current penetration at 10 kHz. Connections to each coil were constructed away from the walls to minimize local disturbances to the magnetic field. The connections to each coil were also made in the center of the coil rather than at a corner to prevent an axial current component which could induce an instability in the plasmoid. The outer coil was tapered to 2 degrees to provide the Lorentz acceleration force, while the inner coil remained cylindrical. Both coils were connected in parallel to the main bank capacitor, so that the voltage drop across the coils remained equal. The plasmoid was contained between vacuum sealed quartz liners, held off the walls by magnetic pressure. In the event of translation, the plasmoid exhausted into Chamber 5B, a stainless steel vacuum chamber 1 m in diameter and 2 m in length.

The current pulse required to form the plasmoid was created by releasing the energy stored in a capacitor into the inductive coils, through a National Electronics 7703 ignitron switch. The capacitor was a high voltage, 225- μF electrolytic capacitor. The cathode of the ignitron switch was fixed to the capacitor casing, connected to ground through its firing unit. The anode of the capacitor and the anode of the switch connected to the coils through low inductance lines. The lines were insulated 3-inch wide copper sheets, sandwiched together to minimize spacing and parasitic inductance. The undamped RLC discharge circuit rang at 9.1 kHz through 2-4 cycles. Capacitor voltage was recorded using an isolated Fluke multimeter, connected to a voltage divider circuit between the terminals of the capacitor. The voltage divider circuit was calibrated at DC using a high-voltage Tektronix 6015A probe.

The XOCOT-T3 data acquisition system was a 16-channel, high-speed oscilloscope network, with two Tektronix 8-bit, 4-channel, 125 MS/s oscilloscopes and one Nicolet Sigma 8-channel, 12-bit, 100 MS/s oscilloscope. The oscilloscopes were located inside a grounded screen room behind Chamber 5B.

The principle diagnostics for this work were magnetic field probes (b-dot probes). B-dot probes record a voltage proportional to the rate of change of B-field, as shown in Equation 1.

$$V_{probe} = nA \frac{dB}{dt} \quad (1)$$

The proportionality constant nA is a probe-specific constant related the number of turns n and the cross sectional area A . The XOCOT-T3 used 13 b-dot probes on the outer coil and 6 b-dot probes on the inner coil, as shown in Figure 4. Probe spacing for each set of probe was 1 inch. All probe ends were twisted tightly and connected to twisted-shielded pair just outside the coils. The twisted-pair cables (20 feet long) had a characteristic impedance of 56 ohm.

The desired nA for the XOCOT-T3 experiment was $1 \times 10^{-3} \text{ turns-m}^2$. To match this number and maintain physical clearance, the outer coil probes were wound on flexible 1/16"-thick-1"-wide plastic forms. The inner coil probes were added after the experiment was constructed. They were designed to be used as internal probes for future work, so they had to be small to minimize perturbations to the plasmoid and retain a large nA . Commercial surface mount (SM) inductors are ideal for this application since they use many turns around a small area. The inner coil probes were selected as 8.2 μH SM wire-wound, ceramic core inductors (Coilcraft p/n 8102-10X). These probes were chosen for their small physical dimension (2 mm by 2 mm) and high inductance. Their nA was provided by the manufacturer as $2.13 \times 10^{-4} \text{ turns-m}^2$ and though it was less than the desired nA , it was the largest nA for the probe size. The inner coil probes were sheathed inside a 7 mm OD quartz tube and placed on the outer surface of the inner insulator.

B-dot probes must be calibrated to find nA , if nA is not well known. Surface mount inductors have a well-characterized nA which can be directly obtained from the manufacturer. This type of probe does not require calibration. The outer coil probes were calibrated prior to use to find nA . The most popular method for calibration involves placing the probe inside a Helmholtz coil, where the field is uniform and well known. However, the large external probes used here would not fit inside a Helmholtz coil of sufficient resolution, so the probes were calibrated after they were installed in the experiment. An array of SM probes, identical to

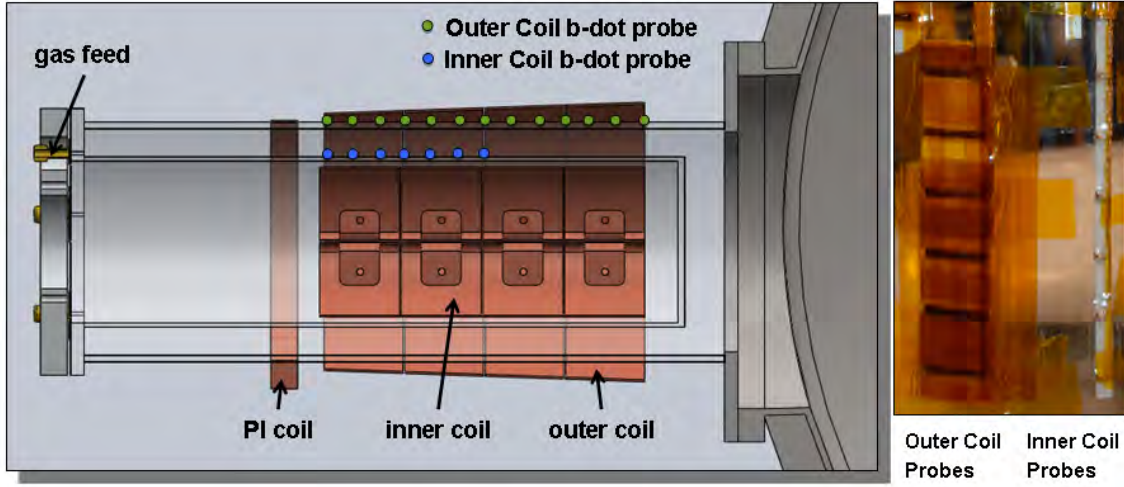


Figure 4. Magnetic field probe locations in the XOCOT-T3 experiment (left) and photographs of external and internal magnetic field probes (right). The photograph does not show the location of the inner coil probes; the probes shown are identical to the inner coil probes but were used for calibrating the outer coil probes.

the inner coil probes ($nA: 2.13 \times 10^{-4} \text{ turns-m}^2$) were installed with the external probes. Current was applied to the coils, measured on each coil using a current monitor (Pearson p/n 301X). The probe voltages were compared and the external probes' nA was calculated as $(nA) * V_{SM} / (nA)_{SM}$. The calibration constants of the SM inductors were checked using a Helmholtz coil calibration prior to use and were found to be within ± 10 percent of the manufacturer's specifications.

For the data collection, the entire raw signal of the b-dot probes were recorded. The probe inductance combined with the estimated capacitance of the long cables resulted in a resonant frequency of 1-2 MHz. Filtering the signal using an analog filter at 500 kHz could attenuate the high frequency resonance, however it was also found to add an approximately 500 ns phase delay to the signal. The probe signals were acquired by the 12-bit Nicolet oscilloscope to reduce offset integration errors and terminated into 50-ohms prior to digitization.

An intensified CCD high speed digital camera was used to image the plasma formation. The digital camera is a DiCAM-2, with a minimum exposure time of 5 ns. A 480 nm, 10 nm bandwidth filter was added to camera to isolate a set of Ar II emission lines. The camera was pointed along a line parallel to the z-axis of the experiment so that an end-on view of the plasmoid could be imaged. The camera had to be positioned to view only a portion of the plasmoid; the perspective of the inner coil prevented the entire plasmoid from being imaged.

The coil currents were measured using wide-band current monitors (Pearson Electronics p/n 301x). This diagnostic can be used to estimate the energy deposition into the plasma by comparing the difference in plasma and vacuum currents. Energy dissipated in the plasma can be calculated by a simple energy balance: $E_{in} = E_{circuit} + E_{plasma}$. The input energy E_{in} is the energy initially stored in the capacitor and the circuit energy $E_{circuit}$ is the energy dissipated by the circuit's ohmic losses $\int I^2 R dt$. The circuit resistance R can be calculated from the vacuum current or the current in the circuit without a plasma load. The energy into the plasma can then be calculated by:

$$E_{plasma} = \frac{1}{2} C V_{charge}^2 - R \int (I_{inner} + I_{outer})^2 dt - \frac{1}{2} C V_{final}^2 \quad (2)$$

In equation 2, I_{inner} and I_{outer} are the currents through the coils with a plasma load, V_{charge} is the initial charge voltage on the capacitor, C is the circuit capacitance, and V_{final} is the voltage remaining on the capacitor after the desired time interval. The energy dissipated by the plasma calculated by this method includes all losses (ionization, radiation, inelastic collisions, etc), but gives an idea of the global energy deposition. A more complicated energy analysis requires more sophisticated measurement techniques and models.

Additional diagnostics for the XOCOT-T3 include a wideband photometer for measuring qualitative

light output and a Rogowski coil for measuring the PI current (Stangenes Industries p/n 2-0.1WA).

IV. Results and Discussion

In a typical discharge, the plasmoid creates an inductive load on the circuit and increases the frequency of the circuit as shown by the coil currents in Figure 5. The dashed lines are the current without plasmoid formation and the solid lines (vacuum shot) with a plasmoid present (plasma shot).

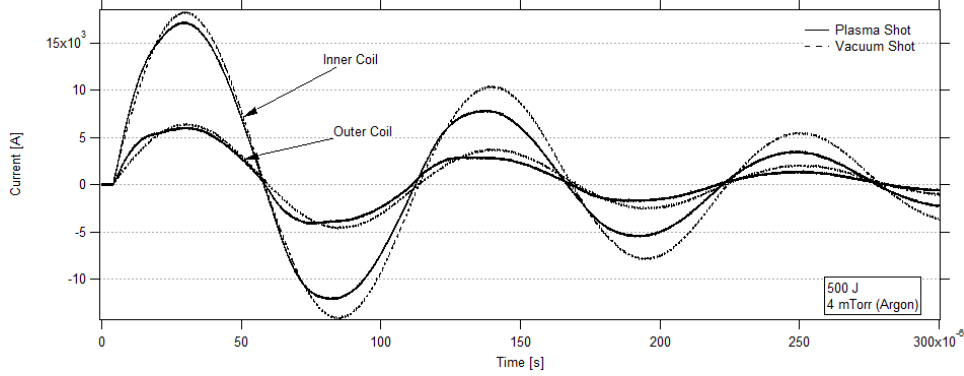


Figure 5. Inner and Outer coil currents for a plasma shot (solid) and a vacuum shot (dashed) during a typical pulse. The plasmoid creates an inductive load on the circuit, as noticed by the frequency change. A reduction in amplitude is a result of energy absorption from the plasmoid formation.

From this data, it is apparent that the plasmoid is well coupled to the coils. Additionally, the plasmoid formation draws energy from the circuit. The total energy consumed by plasmoid formation can be estimated by integrating the power dissipated in the circuit, as shown in Equation 2. This was done for each operating condition tested for the first half-cycle of the pulse to find an optimal operating condition.

The range of operating conditions tested in the XOCOT-T3 was pulse energies of 100 J to 500 J and pressures of 1 mTorr to 20 mTorr. The energy deposited into the plasma during the first half-cycle of the discharge was calculated using equation 2. The circuit voltage was calculated from the capacitor current: $V(t) = -\int I dt/C$. Figure 6 shows the results for the energy deposition. The energy per mTorr of fill pressure is also shown.

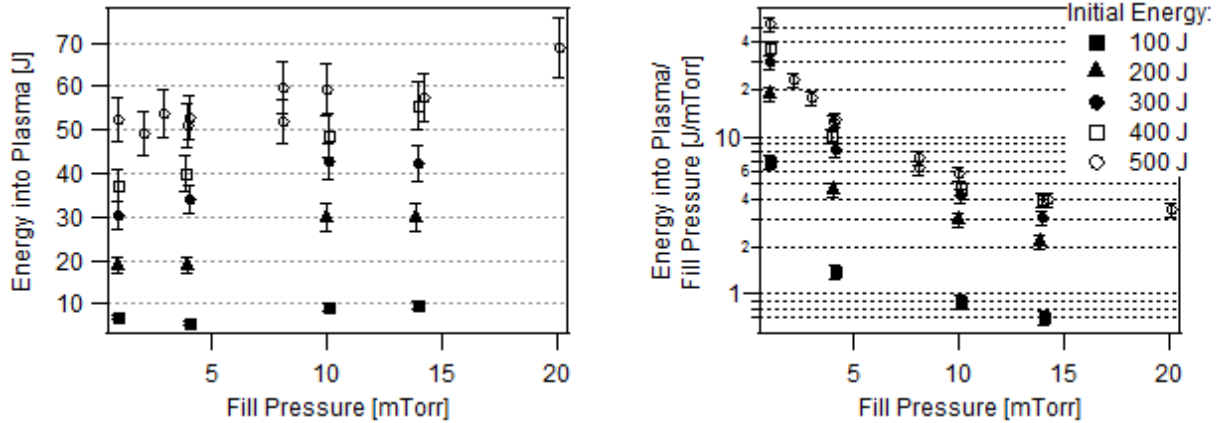


Figure 6. Energy deposition into the plasma for various pulse energies and fill pressures for the first half-cycle of the pulse. This data shows that higher fill pressures absorb less energy per neutral fill atom from the coils, suggesting optimal formation/translation occurs at low fill pressures.

The error bars in Figure 6 represent a 10 percent confidence interval, as found from scatter in the data at repeat operating conditions. The results in Figure 6 show that the total energy absorbed by the plasma is sensitive to pulse energy. This is expected as ionization in inductive devices is related to dI/dt ; maximizing

the energy into the circuit should result in high ionization and large current drive. However, the data also shows that the total energy absorbed is not sensitive to fill pressure. This means that the lower fill pressure (1 mTorr - 4 mTorr) cases absorb more energy from the coils per neutral fill atom. For translation, this indicates that lower fill pressure plasmoids will be more likely to translate because of their higher energy content/mass ratio (assuming the energy loss mechanisms don't vary widely over this range of pressures).

From this data, the operating condition most likely to exhibit translation is the case at moderate energy (500 J/pulse) and low fill pressure (4 mTorr). This case was chosen as the nominal operating condition for the XOCOT-T3 and will be presented in more detail below.

Figure 7 shows the magnetic field, coil currents, and photometer signal for the nominal operating conditions. A plasmoid is generated when the coils dI/dt reaches a local maximum or minimum. The presence of a plasmoid generates a reversed field on the inner coil probes, as compared to the outer coil probes. Without a plasmoid, both probe signals have the same orientation and the same phase since they both measure the field contributions from the outer coil. Plasmoid formation is also indicated qualitatively by large ionization events, registered as light output on the photometer signal.

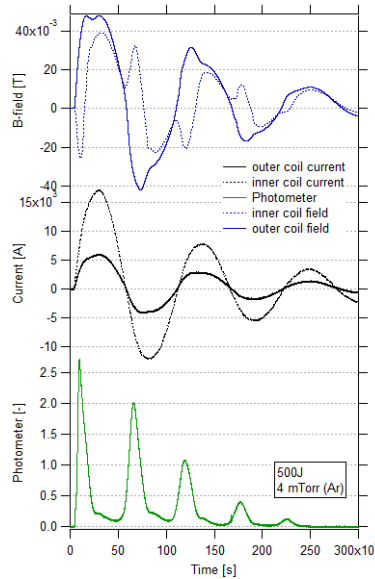


Figure 7. Magnetic fields, coil currents, and photometer signal for a 4 mTorr, 500 J discharge in Argon. The entire pulse duration is shown in this data, with a plasmoid formation every 50 μ s.

For nominal operating conditions, one plasmoid is generated every 50 μ s. The plasmoid disappears shortly after loss of field reversal when the magnetic fields on the inner and outer coils register a unidirectional field and return to the vacuum condition. Figure 8 shows the magnetic field reversal in more detail by graphing magnetic field data from several inner coil probes and several outer coil probes for nominal operating conditions for the first quarter cycle of the main bank pulse.

Plasmoid translation can be inferred by comparing the signals for the outer coil probes at $z = 2$ inches (B2) and $z = 10$ inches (B10). In the event of translation, there should be a marked time delay between features in these signals. A plasmoid traveling at 10 km/s would require a transit time of at least 20 μ s between the probes. The B2 probe signal should return to the vacuum field 20 μ s before the B10 probe. Evidence of this in the data is not seen. Additionally, it appears that the reversed field is only present for 10 μ s, reaching its peak about 5 μ s into the pulse. This seems to indicate the plasmoid is lifetime limited and may be the reason translation does not happen.

Filtered high speed images were recorded of the plasmoid formation using the high speed digital camera. These images are shown in Figure 9. Ionization is apparent at 6 μ s, with plasma filling the annulus. At 9 μ s, a bright ring of plasma appears well centered between the coils, though a diffuse glow appears around it. The ring fades starting at 18 μ s and by 20 μ s has mostly disappeared.

The images do not show a gross plasma instability which would limit lifetime; the plasmoid ring is fairly coherent within the viewing area. Additionally, the bright ring of plasma indicates the plasmoid confinement remains centered in the annulus up until 20 μ s, when it comes in contact with the inner insulator. Magnetic

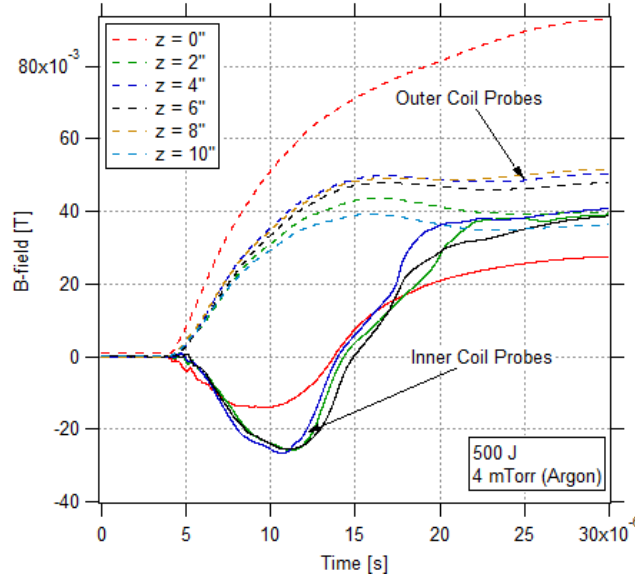


Figure 8. Detail view of axial magnetic field probes space along the inner and outer coil. Plasmoid translation is not evident as there is no marked time-delay between the axial probes.

pressure is responsible for balancing the plasmoid between the coils and the plasmoid is expected to travel radially when the pressure balanced is lost. Comparing 9 and 8, it is apparent the plasmoid remains centered even when there is no magnetic pressure on the inner coil. It is possible that while the plasmoid has disappeared (as indicated by magnetic field probe signatures), the plasma remains localized to the region it was created. Diagnosing radial stability from images alone is difficult as images can only show ionization events.

V. Future Work

A full data set on the XOCOT-T3 at one operating condition has been presented. The experiment needs to be tested through its full range of available conditions before conclusions on plasmoid translation can be finalized. Future work will test the experiment across a range of pressures (1 mTorr - 50 mTorr) and increased energies up to 1 kJ. Additionally, research efforts will investigate the limited lifetime of the AFRC plasmoid. Since little is known about the temperature and density profiles of the XOCOT-T3 plasmoid, this data will be collected in the coming months and will help estimate the energy content of the plasmoid.

VI. Conclusion

Preliminary results from the XOCOT-T3 experiment at 500 J and 4 mTorr show a well formed plasmoid which magnetically couples to the discharge circuit. Magnetic field probes on the inner and outer coil show the field on the inner coil reverses, reaching a peak 5 us into the pulse. The reversal is lost at 10 us and the ionization from the plasma disappears at 20 us. The plasmoid does not appear to translate from the coils or undergo a gross instability. Instead, it suffers from a short lifetime based on the magnetic field probe signatures. Future work on the XOCOT-T3 will concentrate on changing the operating conditions (pressure and energy) to see if plasmoid translation at higher energy is possible.

Acknowledgments

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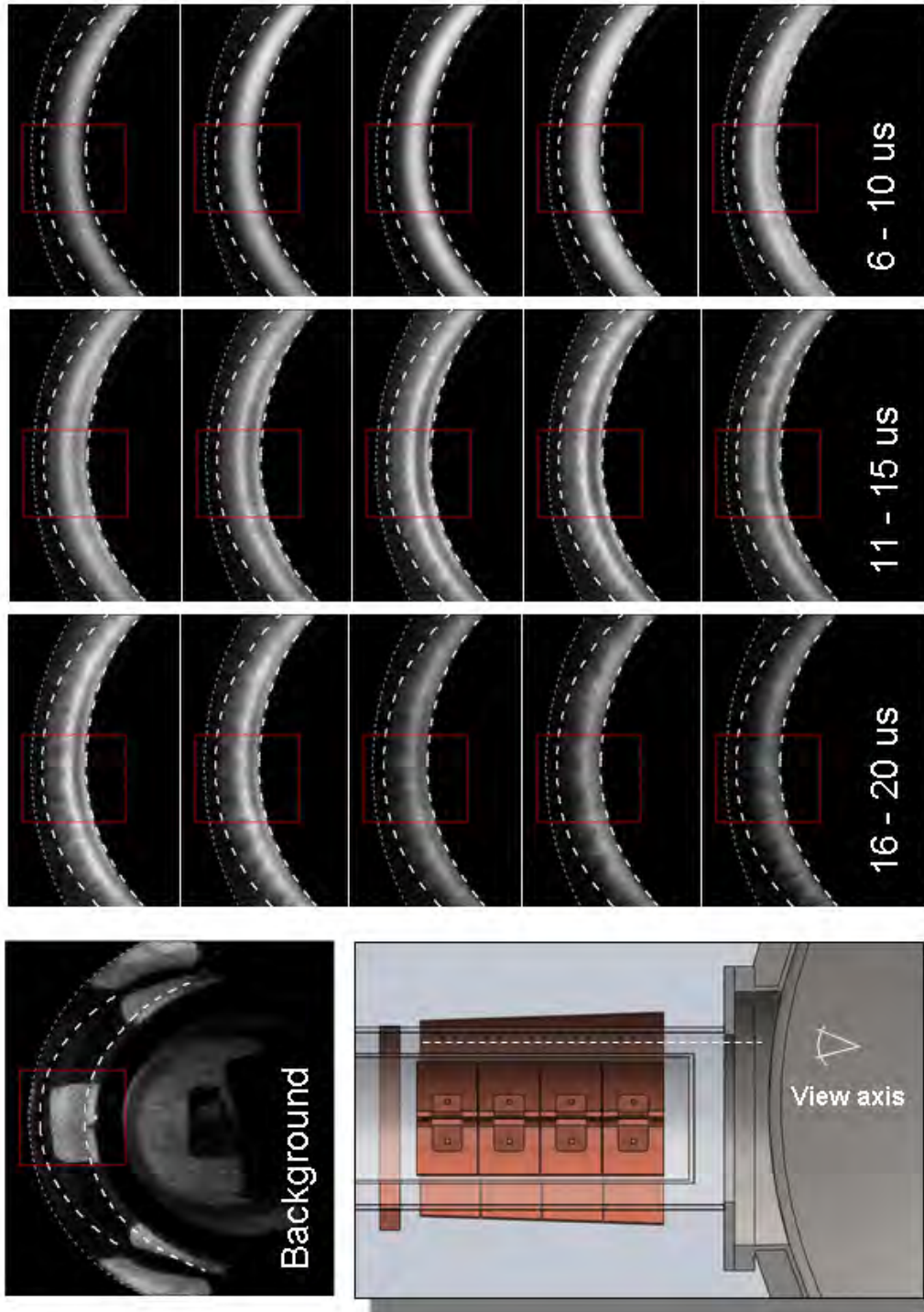


Figure 9. High speed photography of the plasmoid formation in the XOCOT-T3. These images do not indicate a gross plasmoid instability and show a well-centered ring between the coils (thick dashed lines). The outermost thin dashed line is a tank boundary, indicated for reference.

ments extend to Mr. Greg Azarnia (ERC, Inc.) for constructing the magnetic field probes used in this research.

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